SRF Experience with the Cornell High-Current ERL Injector Prototype

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Cornell University
<table>
<thead>
<tr>
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<th>M. Liepe</th>
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<tbody>
<tr>
<td>S. Belomestnykh</td>
<td>V. Medjizade</td>
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<td>E. Chojnacki</td>
<td>D. Meidlinger</td>
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<td>B. Clasby</td>
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<td>Z. Conway</td>
<td>P. Quigley</td>
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<td>R. Ehrlich</td>
<td>J. Sears</td>
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<td>D. Heath</td>
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Cornell ERL:
5 GeV, 100 mA X-ray light source
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A 100 mA SRF Injector Cryomodule for the Cornell ERL X-ray Light Source
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A 100 mA SRF Injector Cryomodule for the Cornell ERL X-ray Light Source
Outline

• Introduction
• Injector Module Design and Innovations
• Beamline Components and Module Assembly
• Cool down, Alignment, Static Loads
• RF System Commissioning
• Initial SRF Performance
• LLRF Field Control
• Cavity Microphonics and Frequency Control
• ERL Injector Cryomodule and Beam Studies
• Outlook
Introduction
• Energy gain: 5 to 15 MeV
• High cw current:
  – 100 mA (77 pC/bunch) @ 5MV, 0.5 MW
  – 33 mA (26 pC/bunch) @ 15MV, 0.5 MW
• High beam power \leq 0.5 MW
• Short bunch length: 0.6 mm (2 ps)
• Very low emittance \varepsilon_n = 0.1-2 \text{ mm-mrad}

⇒ Well beyond present state-of-the-art!
• **1.3 GHz SRF 2-cell cavities:**
  - 5 cavities
  - 5–15 MV/m to deliver 500 kW power total to the beam
  - Number of cells limited by max. input coupler power

• **RF system:**
  - 2 coax couplers per cavity for symmetry (twin-coupler)
  - One 120 kW CW klystron per coupler pair
• Beamline HOM Loads for aggressive damping of HOM’s generated by high current and short bunches

• Symmetric beam line for emittance preservation:
  – Twin coax input couplers
  – Round beam line absorbers (no HOM loop couplers)
  – Cold cavity fine-alignment

<table>
<thead>
<tr>
<th>Numb. of cavities / HOM loads</th>
<th>5 / 6</th>
</tr>
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<tbody>
<tr>
<td>Accelerating voltage per cavity</td>
<td>1 - 3 MV</td>
</tr>
<tr>
<td>Fundamental mode frequency</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>R/Q (circuit definition) per cavity</td>
<td>111 Ohm</td>
</tr>
<tr>
<td>Loaded quality factor</td>
<td>$4.6 \times 10^4$ to $10^6$</td>
</tr>
<tr>
<td>RF power installed per cavity</td>
<td>120 kW</td>
</tr>
<tr>
<td>Required amplit. / phase stab. (rms)</td>
<td>$1 \times 10^{-3}$ / 0.1°</td>
</tr>
<tr>
<td>Maximum beam current (design)</td>
<td>100 mA</td>
</tr>
<tr>
<td>Total 2K / 5K / 80K loads</td>
<td>$\approx 26 / 60 / 700$ W</td>
</tr>
<tr>
<td>Overall length</td>
<td>5.0 m</td>
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ERL Injector Schedule

- **August 2007**: Single-cavity horizontal test cryomodule
- **September 2007**: Beam line and cryomodule assembly starts
- **October 2007**: All cavities, tuners, HOM absorbers, and input couplers are fabricated and tested
- **February 2008**: All cryovessel parts fabricated
- **March 2008**: Cryomodule assembly is finished
- **April 2008**: Module installation in ERL injector prototype and cool down
- **June 2008**: First RF
- **July 2008**: First beam
Injector Module Design and Innovations
ERL Injector Cryomodule

• Use the well-established platform of TTF technology to reduce risk and minimize development time
  – Cavities supported by large diameter Helium-gas return pipe (HGRP)

• Significant modifications for ERL specific needs:
  – Necessary modifications
    • Much higher beam current beam (100 mA, non-pulsed) ⇒ HOMs...
    • Much higher (100 kW per cavity) average power transferred to the beam
    • Much higher cryogenic loads
  – Innovations
ERL Injector Cryomodule

HGRP system with 3 sections

- Frequency tuner ⇒ Adjust cavity frequency
- HOM absorber ⇒ Damp Higher-Order Modes
- Input Coupler ⇒ Couple RF power into cavity
- RF cavity Inside He vessel

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• Necessary changes compared to a TTF cryomodule:
  – Increased diameter of 2K He pipes for high dynamic CW cavity loads
  – Direct gas cooling of chosen 5K and 80K intercept points
  – No 5K shield, only a 5K cooling manifold
  – HOM absorbers between cavities
  – Improved magnetic shielding with 3 shield layers
  – New end-cap and feed-cap concept with reduced length
ERL Injector Innovations (I)

- Tuner stepper replaceable while string is in cryomodule
- Rail system for cold mass insertion into Vacuum Vessel
- In-situ bake of “warm” coupler sections
- Gatevalve inside of module with outside drive
ERL Injector Innovations (II)

- Precision fixed cavity support surfaces between the beamline components and the HGRP ⇒ easy “self” alignment
- Cavity-subunits can be fine-aligned while cavities are at 2K (if required)
Module Assembly

- Beam Line Components
  - String assembly
- Cold mass assembly
**SRF cavities:**
- Designed, fabricated, prepared and tested at Cornell
- Only BCP, no 800C
- All cavities met 15 MV/m spec

**RF input couplers:**
- Design by Cornell for high cw power > 50 kW
- 2 prototypes tested up to 60 kW cw, 80 kW pulsed
- 10 production couplers supplied by industry
Beam Line Components (II)

HOM absorbers:
- Design by Cornell for strong, broadband HOM damping
- 6 production loads fab’ed by industry

Frequency tuners:
- Modification of the INFN blade tuner
- Added piezos for microphonics compensation (R&D)
- 6 units fabricated by industry
Along the Way: The Test Cryomodule

- *Single* cavity test version of full injector module
  - Same concept,…
  - … just shorter
  - spare 2-cell cavity
  - spare tuner
  - prototype HOM loads
  - prototype couplers

- Tested successfully in 2007
Beamline String Assembly

Attach cold couplers to beamline string

Cavity
He vessel pump port
Cold coupler
Beamline HOM load

Gate valve internal to cryomodule
Cleanroom assembly fixturing
Vacuum vessel interface flange
Cold Mass Assembly at Cornell University (I)

**Beamline string rolling under HGRPs**
- Superinsulated HGRPs
- 2K 2-phase pipe
- Beamline string on assembly fixture extracted from clean room

**Instrumentation**
- 80K manifold
- Coax RF instrumentation
- 80K circuits to HOM loads and RF couplers
- Cold couplers with protective caps
- Temperature sensor wiring

**Cold mass assembly**
- 1100 aluminum 80K shield
- 5K manifold
- 2K 2-phase pipe
- Magnetic shield II

**80K shield**
- Beam entrance gate valve
- 1100 aluminum 80K shield
- Instrumentation ports
- RF coupler ports
Cold Mass Assembly at Cornell University (III)

Insight from the Assembly:
- First assembly revealed no significant design problems
- Fast, easy assembly (once we had all parts)
- Fixed cavity alignment concept works well
- Full 3D modeling (including assembly drawings) extremely helpful
Injector Module installed in the ERL Prototype

- Refrigeration transfer lines
- Waveguide feeds from klystron
- Beam exit
Test Infrastructure

- 135 kW cw power klystron (e2v)
- Cold-box with 2K, 5K, 80K heat exchanger
- 120 W @ 2K pumping skid/refrigerator
Cool-down and Cavity Alignment and Static Heat Loads
**ERL Injector Cooldown**

- Injector cryomodule cool-down to 4.2K in 2.5 days to minimize thermal stresses (<10 K/hour)
- No vacuum or cryogen leaks

![Graph showing temperature over time](chart)

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Cavity Position Shift During Cool-Down

Wire Position Monitor (WPM) Datalog

Expected $\delta x = 0.38$ mm, observed $\delta x = 0.58$ mm

Expected $\delta y = 0.94$ mm, observed $\delta y = 0.81$ mm

Cavity string is aligned to $\pm 0.2$ mm after cool-down!
Static Heat Leak to 1.8 K

- Measured by closing the JT valve in the LHe feed and measuring the LHe boil-off rate.
- Heaters on the 1.8K system were used for calibration.
- Measured: 10.3 ± 2 W
- Expected: 9 W
- Dominating part of this static heat load comes from thermal conduction from "4.5K intercepts" in the input couplers, support posts and HOM loads to the 1.8 K system.
- "4.5K system" of the cryomodule is currently at an elevated temperature of about 6K (non-ideal heat exchange in the refrigerator system)
  \[\Rightarrow\text{increases total 1.8K static load from } 5\text{ W to } 9\text{ W.}\]
• After cool-down, **frequency spread between cavities was only 17 kHz!**

• All 5 cavities easily powered to minimum gradient of 5MV/m within minutes

• **All 5 cavities showed** \( Q \approx 1 \cdot 10^{10} \) **at 1.8K shortly after cool-down**
RF System Conditioning
120 kWCW RF Klystrons

- 7-cavity K3415LS tube manufactured by e2v
- 5 klystrons, each delivering up to 120 kW of CW RF power to individual cavities via twin input couplers
- Saturated output power of about 160 kWCW
- To provide stable regulation of the cavity field, the klystron must have a non-zero gain and therefore cannot operate in saturation.
- The klystrons passed the factory acceptance test meeting specifications at 135 kW before shipping
- The tubes were installed, tested again at Cornell, and are performing well
Transfer Curves of the K3415LS Klystrons

- Efficiencies exceeding 50% at 120 kW output power

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RF Input Couplers (I)

- All twin input couplers have so far been processed in pulsed mode up to 50 kW under full reflection.
- None of the input coupler parts were baked after final assembly to the beam line.
- The “warm” part of the couplers can be baked in situ via heating elements installed on the couplers in the module, if it should be required to reach power levels above 50 kW.
• All couplers conditioned well, reaching 50 kW in pulsed operation under full reflection within 25 to 75 hours of processing (RF on time).
SRF Cavity Performance in the ERL Injector Cryomodule
SRF Cavity Performance

- Initial cavity performance looked good \((Q \approx 1 \cdot 10^{10} \text{ at } 1.8K)\)
- But: more detailed measurements later showed low intrinsic quality factors \(Q_0\) for all 5 cavities
- \(Q\) degradation over time?
- Currently, the total voltage of the module is limited to 14 MV by cryogenics \((\sim 12 \text{ MV/m})\), close to maximum specification of 15 MV.
- Cavity processing is ongoing to further increase maximum field gradients
- Pulsed gradients: 16 to 24 MV/m (BCP treated cavities)
Intrinsic Q vs. $E_{acc}$ at 2K

- Field emission at higher $E_{acc}$
- Voltage limit due to the chimney heat flux transfer, not quench
- Cavities on either end of the module show lowest Q
**Cause of low $Q_0$**

- Likely several contributors
- First simulations and measurements indicate that losses in the beam tube and coupler regions contribute significantly to the overall dynamic cavity losses
- Cavity flanges are thermally anchored to a "4.5K" cooling circuit
- But: "4.5K" system is currently at 6K (inefficient heat exchanger in cold box)
  \[ R_{BCS} \propto \exp(T) \]
Intrinsic quality factor Q vs. $E_{acc}$ for all cavities together

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LLRF Field Control
LLRF Field Control

- LLRF electronics for the ERL injector is a new, improved generation of LLRF system previously developed for CESR
  - Faster hardware for lower loop latency (<1μs)
  - Increased ADC resolution (16 bits)
- Performs well with excellent field stability
- LLRF electronics also used to measure
  - Beam current amplitude and phase noise (using BPM signals)
  - Soon: beam position in module via HOM probe signals on the HOM loads between cavities
- Detailed studies of LLRF gain/stability and microphonic noise are under way
Gain Optimization for PI Field Control Loop

Excellent field stability achieved: amplitude: $\sigma_A/A < 2 \cdot 10^{-5}$

phase: $\sigma_P < 0.01$ deg

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Main source of field perturbation is a strong ripple on the klystron HV
Ripple has relative amplitudes of several percent and frequencies ranging from 360 Hz to may kHz.
Cavity (De)tuning
**SRF Cavity Frequency Tuner**

- Modification of the INFN blade tuner
- Tuning range:
  - 500 kHz stepper
  - 500 Hz piezo
- Added piezos for microphonics compensation (R&D for ERL main linac)
• Tuned 100,000 steps (300 KHz)

• LLRF system can easily detect fields with cavity detuned by several >500 bandwidths!

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Microphonics in the Injector Module

- Significant changes over time
- Step impulses related to cryo-system?
Microphonics Histogram

Measured during “step-impulse free time”

- Graph shows histogram of 30 Million samples over a period of 1 hour
- $\Delta f_{\text{max}} < 5^*\sigma_f$
- No extreme outliers

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Mechanical Coupling Characterization
Measurements with a Modal Shaker

Shaker on module support

Response ampl. [arb. units]

Vibration frequ. [Hz]

Shaker on module top (HGRP support)

Response ampl. [arb. units]

Vibration frequ. [Hz]
### Mechanical Coupling Characterization Measurements with a Modal Shaker

<table>
<thead>
<tr>
<th>Excitation Point</th>
<th>Excitation Force</th>
<th>Detectable With Cavity Accelerometer</th>
<th>Detectable On Cavity RF Frequency (&gt;0.1Hz modul.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupler Waveguide</td>
<td>110 N (25 lbs)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Coupler</td>
<td>110 N (25 lbs)</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Cryomodule Saw-Horse</td>
<td>110 N (25 lbs)</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>Support</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium Gas Return Pipe</td>
<td>110 N (25 lbs)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Support</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Beam Line</td>
<td>10 N (2 lbs)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Helium Supply/Return</td>
<td>110 N (25 lbs)</td>
<td>No</td>
<td>No</td>
</tr>
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</table>

- Ground vibrations and other mechanical vibrations do **not** strongly couple to the SRF cavities.

- Main contribution to cavity microphonics comes from fast fluctuations in the He-pressure and the cryogenic system.
Active Compensation of Lorentz-Force Detuning

- Piezo-electric actuators implemented in the cavity frequency tuners
- Used feedback loop for active compensation
- Works very reliably
Active Compensation of Microphonics?

- Microphonics feedback challenging because of complex transfer function piezo $\rightarrow \Delta f$ with mechanical resonances

- This work has just started...
- So far: reached stable control with 20 Hz bandwidth
Beam Measurements

See TU2GRI01
HOM Power

- HOM absorbers allow for measuring the total HOM power excited by the beam
- Heaters on the HOM loads for calibration
- Maximum beam current so far 4 mA -> only a few mW of HOM power/cavity
- At higher bunch charges and currents, several W of HOM power per load!
RF Coupler Kick as a BPM

- Orbit can be estimated by measuring transverse kicks by the RF fields in the input coupler regions.
- The RF field is exited by a forward power of up to 1 kW with strongly detuned cavities.
- By measuring magnitude and direction of the kick to the beam, the beam position in the coupler region can be determined.
250 keV Beam Trajectory determined by RF Coupler Kicks

Very low energy (250 keV) beam

remnant magnetic field?
Summary and Outlook
• Extensive commissioning and testing of the Cornell SRF ERL injector prototype cryomodule has started

• Progresses well

• Future work will focus on cavity conditioning, microphonics compensation, and high beam current effects.
To come: The ERL Main Linac Cryomodule

80K Shield
Top Support Cylinder
Composite Post Support
Gas Return Pipe
RF Coupler

Gate Valve
2-phase Pipe
7-cell cavity
Beamline HOM Load
Quadrupole & Steering Coils

80K Radiation to 1.8K

ε = 2.14e-2 gives 50 mW/m² from 80K to 1.8K

See papers WE6RFP002, TU5PFP051, TU5PF058